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EXPERIMENTAL STUDY OF 10.6 μm LASER EXTINCTION BY ATMOSPHERIC AEROSOL

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ABSTRACT: An experimental study demonstrates that there is a strong uncertainty of the 10.6 μm laser extinction by the spheric aerosol in relation to the same value of visibility or aerosol concentration. However, the data seem to indicate that there is a certain correlation between 10.6 μm laser extinction by atmospheric aerosol and visibility from the statistical point of view. For such a correlation an appropriate expression is given here, and the possible applications in laser engineering are discussed.

1. Introduction

It is widely understood that the major factors which cause the attenuation of 10.6μm laser radiation in the atmosphere include: continuous absorption of vapor molecules, line center resonant absorption of atmospheric CO_2 gas molecules, and absorption and scattering of atmospheric aerosol.

As far as vapor and CO_2 molecule absorption are concerned, a large number of experimental and theoretical studies were done in this area, and some related computing models have been verified in the laboratory[1,2]. Despite the fact that some theoretical problems concerning this topic are yet to be further studied (such as the physical mechanism of vapor continuous absorption), the foregoing computing models have already reached an accuracy sufficient for application in laser engineering.

As for the attenuation of the 10.6 μmlaser by atmospheric aerosol, theoretical calculations made in recent years indicate that there is a high uncertainty in the correlation between the aerosol attenuation coefficient with the 10.6μm laser and the aerosol concentration. This uncertainty primarily originates from the variation in aerosol spectrum types and refraction exponent[3], which, however, has yet to be fully verified experimentally.

In actual atmosphere, how much is this uncertainty? From the angle of statistics, is there a certain correlation between the 10.6μm laser attenuation by aerosol and the aerosol concentration (or visibility)? To investigate these two problems, we measured the 1.06μm laser attenuation in the actual atmosphere. At the same time, we also measured the atmospheric aerosol concentration, CO_2 content, relative moisture, temperature and pressure at the optical path. The measurements were used to study the correlation between aerosol attenuation and visibility by deducting the contribution of CO_2 and vapor absorption to the 10.6μm laser attenuation through calculation.

To avoid over large absorption of the 10.6μm laser by vapor, and ensure the accuracy of aerosol attenuation measurement, the entire measurement process was conducted in winter with only small amount of vapor. In order to acquire visibility data quantitatively, a 6328 A laser attenuation was also measured.

2. Experimental Arrangement and Measurement Technique

The experimental arrangement intended for simultaneous measurement of 6328 A and the 10.6μm laser atmospheric attenuation is shown in Fig. 1. Its transmission end mainly involves a laser source (CO_2 laser device or He-Ne laser device 3); a wave chopper 2; a beam-splitting plate 4; a transmitting telescope 5 and related monitoring device.

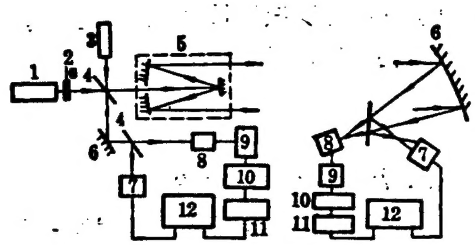

图1 实验装置方框图

Fig. 1 Schematic diagram of experimental arrangement

First, the 6328 A and 10.6μm lasers were adjusted to be coaxial. Both lasers, respectively, were split into two beams through beam-splitting plate 4; one beam was emitted to the atmosphere through a Cassegrain telescope with a diameter 300mm, while the other beam was used to monitor the stability of the laser output power of the laser. The continuous output power of the 10.6μm CO_2 laser (piezoelectric ceramic was applied in controlling the cavity length so that it can operate at P_{20} line) is 1W, and the wave was chopped using a 800 o/s mechanical chopper 2. The continuous output power of 6328 A He-Ne laser 3 is 2mW.

The receiving end primarily consists of a spherical reflector 6 with a diameter 320mm, a beam-splitting plate 4 and a detection recording system. The transmitting telescope focuses a beam on the receiving reflector with a light spot of approximately 15cm in size, and can realize total reception measurement.

Both the transmitting end and receiving end are equipped with the same measurement system. The 6328 A and 10.6μm lasers, respectively, are detected with a photomultiplier cell 7 and a lithium tantalate thermovoltaic detector 8. The output signal from the photomultiplier cell is directly recorded using one pen of the double pen X-Y recorder 12, while the output signal from the lithium tantalate thermovoltaic detector, detected through prepositioned amplifier 9, frequency selective amplifier 10 and detector 11, is recorded with another pen of the recorder.

Prior to measurement of atmospheric attenuation, relative scaling was made in advance for the measurement system of the receiving end and the monitoring system of the transmitting end. Suppose the receiving signals of 6328 A and 10.6μm, respectively, are $I_1^{6328Å}$ and $I_1^{10.6\mu m}$, and monitoring signals are $I_0^{6328Å}$ and $I_0^{10.6\mu m}$ when the propagation distance is zero, then we can define the scaling constant as

$$\xi^{6328Å}=I_0^{6328Å}/I_1^{6328Å}, \tag{1}$$

$$\xi^{10.6\mu m}=I_0^{10.6\mu m}/I_1^{10.6\mu m}, \tag{2}$$

In actual measurement, if the receiving signals of 6328 A and 10.6 μm, respectively, are $I_2^{6328Å}$ and $I_2^{10.6\mu m}$, and monitoring signals, respectively, are $I_3^{6328Å}$ and $I_3^{10.6\mu m}$, the transmittances at the optical path can be derived, respectively, as

$$T^{6328Å}=\xi^{6328Å}I_2^{6328Å}/I_3^{6328Å}, \tag{3}$$

$$T^{10.6\mu m}=\xi^{10.6\mu m}I_2^{10.6\mu m}/I_3^{10.6\mu m}. \tag{4}$$

The attenuation coefficient K at unit length can be computed in accordance with the following formula:

$$k=-\ln T/L, \tag{5}$$

where L is the length of optical path.

During the experiment, the atmospheric aerosol concentration, CO_2 content, vapor content, atmospheric

temperature and pressure at the optical path were measured simultaneously. Among them, the atmospheric aerosol concentration was measured using a ten-channel photoelectric particle counter, which was developed by our institute. In fact, due to the limitation of the instrument's response sensibility, we measured the concentration and spectrum distribution of particles with a radius greater than 0.25μm. The CO_2 content was measured with a FQ-W-CO_2 infrared analyzer, while other meteorological elements were measured by using conventional meteorological instruments.

3. Calculation of Aerosol Attenuation Coefficient with 10.6 μm Laser and Error Analysis

1) Calculation of $k_a^{10.6\mu m}$

To derive the 10.6 μmlaser attenuation caused by atmospheric aerosol, the absorption of atmospheric CO_2 gas and vapor must be deducted from the experimental attenuation value (total attenuation value). The absorption of 10.6 μm CO_2 laser by CO_2 gas (P_{20} line) can be calculated using the following formula[1]:

$$k_{CO_2}^{10.6\mu m} = \frac{6.87x}{\theta^{0.43}Q(\theta)} \exp\left[7.44 - \frac{2233}{\theta}\right] \quad \mathrm{cm}^{-1}, \tag{6}$$

where x is the volume mixing ratio concentration of CO_2 gas in the atmosphere (ppm); Θ is absolute temperature (K); Q(Θ) is partition function. Recently, by using an optical sound technique, we obtained an empirical formula for the continuous absorption of vapor as follows:

$$k_{H_2O}^{10.6\mu m} = \frac{0.267}{\theta} p_{H_2O}[p_{H_2O} + \nu(P - p_{H_2O})] \exp\left[4000\left(\frac{1}{\theta} - \frac{1}{296}\right)\right] \quad \mathrm{km}^{-1}, \tag{7}$$

where $\nu = 0.0034\exp\{7000[(1/296) - (1/\theta)]\}$; p_{H_2O} and P, respectively, are vapor partial pressure and atmospheric pressure (Torr); Θ is absolute temperature (K).

Based on the CO_2 content, vapor content, temperature and pressure recorded during the measurement, we calculated, using Eqs. (6) and (7), respectively, the CO_2 and vapor absorption values in the measured 10.6 μmlaser attenuation value. Therefore, we were able to derive the 10.6μm laser attenuation coefficient by aerosol $k_e^{10.6\mu m}$ from the following formula:

$$k_e^{10.6\mu m} = k_{\Sigma}^{10.6\mu m} - k_{CO_2}^{10.6\mu m} - k_{H_2O}^{10.6\mu m}, \tag{8}$$

where $k_{\Sigma}^{10.6\mu m}$ is the actual measurement value.

2) $k_e^{10.6\mu m}$ Value Error Analysis

The analysis of the $k_e^{10.6\mu m}$ value covers two kinds of errors: one is systematic error, i.e., the $k_e^{10.6\mu m}$ value is systematically over high or over low, which primarily originates from the accuracy of Eqs. (6) and (7). Our experiment demonstrated that the accuracy of the above two formulas is generally better than 8%. During the entire experiment, the atmospheric CO_2 content varied in the range from 290 to 380ppm; the variation range of vapor partial pressure and temperature, respectively, was 3~8 Torr and 271~290 K. In this case, the systematic absolute error of the $k_e^{10.6\mu m}$ value thus obtained will not exceed 0.012 km^{-1} in any case.

The other kind of error is random measurement error, which is reflected in the uncertainty of the $k_e^{10.6\mu m}$ value. This kind of error mainly results from the measurement error of vapor and CO_2 content as well as the relative scaling error of the measurement arrangement. According to scaling of the former, the measurement errors of both CO_2 content and relative moisture were less than 1% so that the uncertainty of the $k_e^{10.6\mu m}$ value caused by the measurement errors of the foregoing meteorological elements can be ignored. While the latter normally can lead to a relative measurement error of transmittance no greater than 3%. Hence, within our measurement range, the maximum random absolute error of the measured attenuation coefficient value $k_{\Sigma}^{10.6\mu m}$ is

0.022 km^{-1}.

In accordance with the above discussion coupled with referring to Eq. (8), the total absolute error of the $k_a^{10.6\mu m}$ value is no greater than 0.025 km^{-1}. As for its relative error, it will increase with the decrease in the $k_a^{10.6\mu m}$ value. For instance, at a visibility distance 5km, the maximum relative error is approximately 26%, while at a visible distance over 15km, the maximum relative error can reach more than 76%. Evidently, for a visible distance over 15km, the present measurement accuracy does not seem to be up to standard.

4. Measurement Result and Discussion

Our experiment was undertaken with a propagation optical path 1.38km and at an average height of around 25m from the ground at the suburbs of Hefei city from November 20 through December 20, 1978. During this period, the variation range of temperature, relative moisture and pressure, respectively, was 271~290 K, 25~80% and 1015~1030mbar. A total of 335 measurements were made in this experiment. Fig. 2 shows the correlation between aerosol attenuation coefficient at 10.6μm laser and the concentration of aerosol particles with a radius greater than 0.25 μm. Each data point in the figure stands for the average value derived through five measurements within 3min.

It can be seen from Fig. 2 that there is a distinct correlation between the aerosol attenuation coefficient at the 10.6μm laser and aerosol particle concentration from the angle of statistics (the linear correlation coefficient is 0.61), yet this correlation suffers from a high uncertainty; especially, when the aerosol concentration exceeds $1.0\times10^5 l^{-1}$, its discretion already surpasses the experimental error to a great degree. The reason for this uncertainty, as stated in reference[3], is probably the variation of aerosol spectrum type and refraction exponent during

the experiment period.

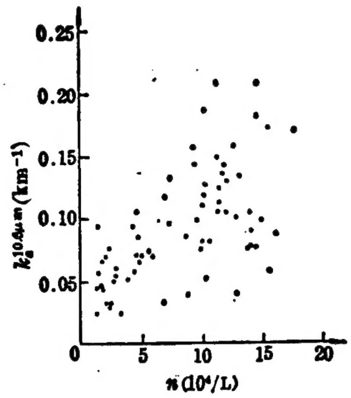

Fig. 2, Correlation between aerosol extinction coefficients at 10.6 μm and aerosol concentration

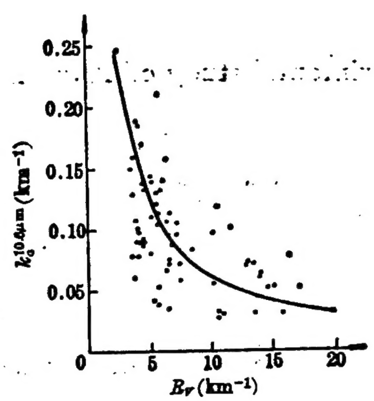

Fig. 3. Correlation between aerosol extinction coefficients at 10.6 μm and visibility

Fig. 3 shows the correlation between aerosol coefficients at the 10.6 μmlaser and visibility, where the visibility distance is derived through conversion of the measured values of attenuation coefficients with the 10.6μm laser using the following empirical formula:

$$R_V = 3.91/k^{6328Å} \quad (9)$$

Fig. 3 suggests that there is certain correlation between them:

the $k_e^{10.6\mu m}$ value increases with the decrease in visibility distance. Based on experimental data, we derived the following empirical formula (the solid line in the figure):

$$k_e^{10.6\mu m} = A/R_V, \tag{10}$$

where A=0.60 with a mean square root error 0.27; attenuation coefficient $k_e^{10.6\mu m}(\mathrm{km}^{-1})$; visibility distance $R_V(\mathrm{km}^{-1})$.

It can also be clearly seen from the figure that the uncertainty of the foregoing correlation is extremely obvious. Even at a visibility distance approximately 15km, the maximum deviation of the data site versus the empirical curve can reach as high as 100%, i.e., much greater than the measurement error (the maximum random error is around 55%). This indicates that to correctly estimate the aerosol attenuation at the 10.6μm laser, it is not enough to describe only with visibility; instead, it is necessary to consider the aerosol spectrum type and refraction exponent under local conditions[3].

However, Eq. (10) is an average statistical result, which can offer the most probable value of aerosol attenuation at the 10.6μm laser and its root-mean-square error at a particular visibility. Therefore, in applying and especially in designing some laser engineering, Eq. (10) can provide necessary data concerning the possible effect of atmospheric aerosol at different visibility.

5. Conclusions

Our experiment tentatively confirmed the theoretical prediction[3], i.e., using visibility (or aerosol concentration) to describe the atmospheric aerosol attenuation at the 10.6μm laser may give rise to a high uncertainty. This uncertainty probably results from the variation of aerosol spectrum type and

refraction exponent. Nevertheless, in terms of statistical averaging, there is a more or less obvious correlation between them. Here in this paper, we proposed an approximate expression of this correlation, which is capable of providing approximate estimation of the aerosol effect in some laser application engineering. Also, we pointed out the possible errors that this approximate expression may lead to.

Among the participants in our experiment were also: Hang Jingchen, Wang Shaoqing, Pu Dasheng, Dou Gendi, and Chen Aizheng.

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